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Quantifying Environmental Flow Requirement Towards Watershed Sustainability

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Humankind is prone to exceeding biogeochemical limits to freshwater resources in the face of rapidly increasing demands of global population and economic growth without a measurable indicator of sustainability. Such indicators with a differing methodological complexity were developed for rivers in order to estimate water quantity required to secure their long-term productive state. Generally, environmental flow requirement method was applied to economically significant rivers where intensive fisheries take place and was defined as the sum of flow requirements that fish stocks demand. Recently, more robust methods for environmental flow requirement have been developed that consider multiple environmental factors such as demands of other organisms (*e.g.*, invertebrates and water birds), ecosystem structure (*e.g.*, biogeoclimate, geomorphology, flora, fauna, biodiversity and flood plain) and ecosystem function (*e.g.*, nutrient cycles, primary production and ecosystem respiration). This study assesses the concept of environmental flow requirement in the context of Big Melen water transfer project as a case study.

Key Words: Adaptive management, Environmental flow requirement, Riverine ecosystems, Sustainability.

INTRODUCTION

Achieving sustainable management of rivers for the long-term health of both ecological and economic systems of a given watershed or country is one of the most crucial issues of the current and future generations, especially in the face of global climate change[1]. Biogeochemical limits to riverine ecosystems cannot sustain rapidly increasing demands of global population and economic growth without a measurable indicator of sustainability. Rivers play a significant role in interconnecting abiotic and biotic ecosystem components as well as terrestrial and aquatic ecosystems just as a biological neural network. Maintenance of natural flow regimes is vital to the sustenance of the ecosystem goods and services for both humans and riverine organisms and economic value of rivers. However, natural flow regimes of over 60 % of world's rivers have been drastically altered at an unprecedented rate due to building of dams, impoundments, withdrawals and diversions[2,3].

The direct and indirect appropriation of rivers can take place in the form of blue, green and grey water uses that refer to consumption of surface and groundwater, consumption and evaporation of rainwater and use of freshwater as a dilution water requirement to assimilate pollution based on existing ambient water quality standards, respectively[4,5]. Blue, green and grey water uses can occur internally or externally depending on water volume imported from other countries or watersheds. Recent estimates for agricultural consumption of global blue water vary between 927 and 1660 $km^3 yr^{-1}$, which accounts for about 85 % of global blue water consumption, in addition to about 3000 to 6000 $km^3 yr^{-1}$ of global green water consumption[6-9].

Water allocation among various competing land uses/covers necessitates release of certain amount of water from a given river ecosystem to other uses without adversely affecting its natural flow regime. Water left in a river ecosystem for maintaining a desirable state refers to instream flow requirement, environmental flow, or environmental flow requirement[10]. Turkey with 625 dams is one of the top ten countries globally that have drastically altered flow regimes according to the number of dams constructed[11]. This study quantifies the concept of environmental flow requirement in the case of Big Melen water transfer project.

Human-induced disturbances of flow regimes of running water systems alter spatio-temporal dynamics of ecosystem structure and function, which in turn determines the sustenance of ecosystem integrity and health (Fig. 1). Environmental flow requirement studies with differing methodological complexities across the world have been conducted towards sustainable management of natural flow regimes since the end of the 1940s in the western United States of America[12]. Generally, environmental flow requirement estimation is applied to economically significant rivers where intensive fisheries take place, thus defining environmental flow requirement as the sum of water requirement that fish stocks demand. Recently, more robust methods for environmental flow requirement have been developed considering multiple environmental factors such as demands of other organisms (*e.g.*, invertebrates and water birds), ecosystem structure (*e.g.*, biogeoclimate, geomorphology, water body shape, flora, fauna, biodiversity and flood plain) and ecosystem function (*e.g.*, nutrient cycles, primary production and ecosystem respiration).

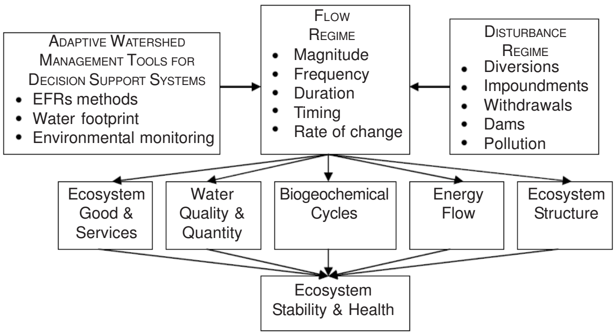

Fig. 1. A heuristic diagram depicting interactions among flow regime, human induced disturbance regime, adaptive ecosystem management tools and ecosystem state

There exist over 207 significantly different environmental flow requirement methods implemented in 44 countries within six regions of the world[13]. Environmental flow requirement methods for either regulated or unregulated rivers may be classified as follows[12,14,15]: (1) hydrological index such as Tennant[16]; (2) hydraulic rating such as wetted perimeter[17] and range of variability approach (RVA)[18]; (3) habitat simulation or modeling such as physical habitat simulation system (PHABSIM)[19]; (4) holistic method such as downstream response to imposed flow transformations (DRIFT)[13,20]; (5) hybrid method such as Basque method[21]; and (6) other methods such as the river invertebrate prediction and classification system (RIVPACS)[22].

Hydrological index is generally used for environmental flow requirement estimates when there is no or inadequate information about how aquatic species respond to variations of hydrological variables and results in low resolution environmental flow requirement estimates and recommendations[12]. Such methodologies as hydraulic rating, habitat simulation and holistic methodology account for habitat and discharge relationships in light of field data collection[10,12]. Hydraulic rating bases environmental flow requirement recommendations on relationships between hydraulic variables (*e.g.*, wetted perimeter and maximum depth) and discharge measured across river cross-sections. Habitat simulation such as instream flow incremental methodology also considers hydraulic and discharge relationships, but analyzes quantity, quality and suitability of instream habitat for target biota under spatially and temporally varying flow regimes, based on integrated hydrological, hydraulic and biological response data. Holistic methods synthesize the other methodologies and addresses environmental flow requirement of an entire riverine ecosystem taking into account such issues as human uses, aesthetic distortion, environmental degradation and environmental costs and benefits of altering natural flow regimes. Hybrid methods combine characteristics of the above methods to make environmental flow requirement recommendations. Other methods includes approaches diverging from the above methods that are generally based on multivariate statistical analyses[12,14,23-25].

Quantifying environmental flow requirements calls for information about trophic interactions and habitat properties of native species and communities and biogeochemical cycles that interconnect ecosystem components[26]. Selection of environmental flow requirement estimation methods may change depending on river flow regime, human attitudes towards ecosystem services, institutional decision support system, social and economic cost of ecosystem analysis and management and data quantity and quality. Most environmental flow requirement methods can be potentially modified to adapt to conditions of different countries, to different types of rivers and to more than one ecosystem component. Methodological limitations that should be considered in the selection and implementation of a particular environmental flow requirement method involve the extent to which assumptions of a given method are met and relaxed and the degree of transferability from one region to another, needs for readily available data, degree of validation across different climate zones and access to documentation and training for use. A greater complexity can be incorporated into environmental flow requirement methods in order to maintain ecosystem structure and function (*e.g.*, fish, riparian trees, water chemistry and biodiversity) at a specified state, accounting for magnitude, timing, frequency and duration of low flows and floods at both spatial scales and intra- and interannual temporal scales of variability[21,26,27].

As for the most recent advances in the quantification of riverine ecosystem health, the utility of a Bayesian hierarchical approach and Bayesian networks was explored to identify responses of rivers as a function of stream flows and regulated environmental flows[28,29]. Modeling and management approaches called 'integrated basin flow assessment' emphasized ways by which environmental flows are managed to achieve watershed-scale sustainability and ecosystem stability of freshwater resources[30]. Also, a new framework termed ecological limits of hydrologic alteration aims at a biome-scale generalization based on relationships between naturally distinctive flow regimes and river ecology such as arid-zone or snow-melt rivers[31]. On the other hand, decision trees were developed to classify natural flow regimes as a function of climatic and topographical driving variables when lack of flow data for streams in a region exists[32,33].

In this study, a novel approach was devised to assess reliability of minimum environmental flow requirement estimates by wetted perimeter method through which it is determined whether or not flow rate at a river cross-section that corresponds to minimum environmental flow requirement estimated by wetted perimeter method is suitable to target species. Thus, target species were first identified according to the following criteria: (1) species under protection, (2) species with economic value and (3) human interference points justified in the ecosystem. Information about the three criteria is derived from related literature and/or field studies. Water velocity and water depth that correspond to wetted perimeter method-estimated flow rate were derived from a rating curve at the cross-section and compared to requirements of target species.

Wetted perimeter method-based minimum environmental flow requirement can be modified accounting for the above considerations.

EXPERIMENTAL

Big melen water transfer project: Big Melen Project aims at transferring to Istanbul 268 million m^3 per year in the first stage and 1.180 billion m^3 per year in the final stage. The big melen project is expected to provide additional drinking and municipal water by a 185-km transfer line. Water diversion from Big Melen stream was initiated in 2007 to meet drinking and municipal water demands of population of additional 2.75 million three years earlier than planned due to prolonged droughts. Total cost of the project is about 1.181 billion USD and the distance from water diversion point to the stream discharge into the Black Sea is about 10 km (Fig. 2)[33].

Wetted perimeter method: In this study, the environmental flow requirement of big melen stream was determined using wetted perimeter method. Wetted perimeter method benefits from the relationship between flow rates and wetted perimeter measured at critical cross-sections (riffle sites) where flow rate and water depth decrease when streambed widens. Wetted perimeter method has such advantages as the lack of intensive field work, ease of application and integration with hydraulic modeling and rapid estimation. However, this method quantifies minimum environmental flow requirement only in terms of the hydrobiological variables of water depth and water velocity and ignores magnitude and severity of impacts on riverine ecosystems when water diversion occurs[14,34-37]. Related literature shows that aquatic organisms respond selectively to differences in flow rate and water depth[38-41].

RESULTS AND DISCUSSION

Monthly mean data between 1981 and 2000 about big melen stream to quantify minimum environmental flow requirement using wetted perimeter method were obtained from the monitoring stations of electrical power resources survey and development administration (EIE) and state hydraulic works (DSI) (Fig. 2) (Tables 1 and 2). The relationship between dimensionless flow rate and wetted perimeter was found using the data presented in Table-2 as follows:

$$\frac{WP}{WP_{max}} = 0.938\left(\frac{Q}{Q_{max}}\right)^{0.1318} \qquad (1)$$

where WP is the wetted perimeter (m); WP_{max} is the maximum wetted perimeter (m); Q is flow rate (m^3 s^{-1}); and Q_{max} is maximum flow rate (m^3 s^{-1}) (Tables 1 and 2). According to eqn. (1), dimensionless flow rate value (Q/Q_{max}) corresponding to breaking point when the first derivative was equaled to unity was estimated at 0.09. It was calculated that minimum environmental flow requirement of big melen stream based on wetted perimeter method (Q_e) $\cong$ 18 m^3 s^{-1} when Q_{max} = 204 m^3 s^{-1} (Table-1). Having determined that, suitability of the minimum environmental flow requirement of big melen stream for target species was assessed.

The following species were selected as target species given their economic value and protection status and water diversion point in big melen stream: *Alburnoides bipunctatus, Leuciscus cephalus, Chalcalburnus chalcoides, Cyprinus carpio, Capoeta capoeta, Barbus plebejus, Esox Lucius, Silurus Glanis* and *Mugil cephalus* (Table-3). For the estimated minimum environmental flow requirement of 18 m^{3}s^{-1}, water depth and water velocity were found to be 1.20 m and 0.34 m s^{-1}, respectively. All the target species in big melen stream prefer habitats with low water velocity and shallow water (Table-3). Thus, there appeared to be no need for a revision of the wetted perimeter method-based environmental flow requirement estimate for big melen stream. The quantity of water to be transferred given the wetted perimeter method-based environmental flow requirement estimate is presented for big melen stream in Table-4.

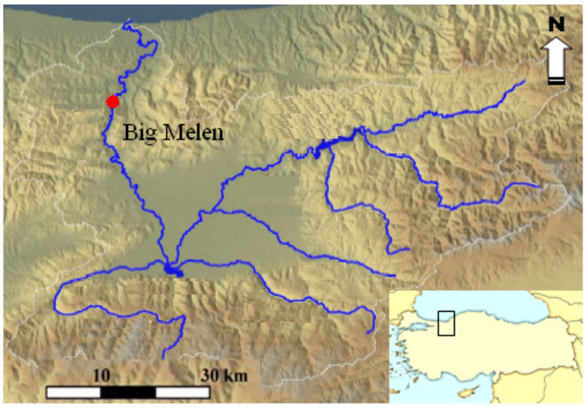

Fig. 2. Study region in western black sea watershed, Turkey

TABLE-1
MONTHLY MEAN FLOW RATES BETWEEN 1981 AND 2000 BASED ON STATION (NUMBERED 1340) OF ELECTRICAL POWER RESOURCES SURVEY AND DEVELOPMENT ADMINISTRATION

Month	Maximum flow rate (m^3 s^{-1})	Mean flow rate (m^3 s^{-1})	Minimum flow rate (m^3 s^{-1})
January	126.0	67.41	28.90
February	139.0	80.55	39.20
March	182.0	93.19	47.40
April	204.0	94.39	18.80
May	164.0	52.74	15.90
June	105.0	31.40	10.70
July	61.9	21.77	5.57
August	48.2	14.63	5.00
September	32.8	13.89	5.06
October	64.6	23.20	8.56
November	102.0	37.36	10.70
December	111.0	63.42	13.10

TABLE-2
RIVER CROSS-SECTION VARIABLES OF FLOW RATE MONITORING STATION BY ELECTRICAL POWER RESOURCES SURVEY AND DEVELOPMENT ADMINISTRATION (EIE)

Q (m^{3}s^{-1})	Stage gauge (m)	Area (m^2)	Wetted perimeter (m)	Mean depth (m)
2.55	0.5	28.31	42.72	0.750
15.3	1.0	48.77	49.17	1.143
62.0	1.5	70.84	53.54	1.558
123.0	2.0	94.80	61.28	1.835
195.0	2.5	121.67	66.80	2.187
270.0	3.0	154.07	77.72	2.281
350.0	3.5	188.21	80.68	2.739
435.0	4.0	222.77	83.12	3.205

TABLE-3
HABITAT REQUIREMENTS OF TARGET SPECIES

Scientific name	Habitat	Preferable flow rate (m s^{-1})	Preferable water depth (m)	Ref.
Alburnoides bipunctatus	Prefers rubble to gravel bottoms; sometimes swims against current; spawns on gravels in flowing water	0.05–0.2	0.4–0.8	38,39
Leuciscus cephalus	Generally spawns on gravel bottoms	<0.05	0.4–0.8	38,39
Chalcalburnus chalcoides	Spawns on rubble to gravel bottoms of fast flowing streams	No data	No data	39
Cyprinus carpio	Prefers slow flowing habitats; spawns on vegetated substrata in very calm and shallow water	<0.2	<0.5	39,40
Capoeta capoeta	No data	No data	No data	
Barbus plebejus	Prefers fast flowing water and sandy bottoms	No data	No data	39
Esox lucius	Lives in bream zone of streams; prefers reedy and weedy habitats with low water flow	<0.05	>0.8	38,39,41
Silurus glanis	Lives in bream zone of streams; prefers muddy bottoms of slow flowing streams	No data	No data	39
Mugil cephalus	Generally prefers spawning habitat as clean and shallow water	No data	No data	39

TABLE-4
WATER QUANTITY TO BE SAFELY TRANSFERRED FROM BIG MELEN STREAM GIVEN BIG MELEN WATER TRANSFER PROJECT AND WETTED PERIMETER-BASED MINIMUM ENVIRONMENTAL FLOW REQUIREMENT

Month	Mean flow rate observed ($m^3 s^{-1}$)	Water quantity to be safely transferred according to this study[a] (m^3s^{-1})
January	67.41	49.41
February	80.55	62.55
March	93.19	75.19
April	94.39	76.39
May	52.74	34.74
June	31.40	13.40
July	21.77	3.400
August	14.63	-
September	13.89	-
October	23.20	4.840
November	37.36	19.36
December	63.42	45.42

[a] Water quantity to be safely transferred from big melen stream was found subtracting minimum EFR (18 m^3s^{-1}) from monthly mean flow rate

Transferring water quantity after ensuring the minimum environmental flow requirement of big melen stream at the mouth of water diversion (18 m^3s^{-1}) is most likely not to adversely affect ecosystem health associated with water velocity and water depth. Given the mean water transfer of 8.50 $m^3 s^{-1}$ projected during the first stage of the big melen project, water diversions in critical months of 3.40 $m^3 s^{-1}$ in July or 4.84 $m^3 s^{-1}$ in October, without water diversion in August and September appear to meet safe minimum standards for big melen stream. Likewise, considering the water transfer amount of 37.50 $m^3 s^{-1}$ by the completion of the project, water withdrawal of 34.74 $m^3 s^{-1}$ in May, 13.40 $m^3 s^{-1}$ in June, 3.40 $m^3 s^{-1}$ in July, or 4.84 $m^3 s^{-1}$ in October, without water withdrawal in August and September appears not to have adverse impacts on the riverine ecosystem. The safe water transfer amount from Big Melen stream in accordance with the estimated minimum environmental flow requirement was, on average, estimated at 32 $m^3 s^{-1}$, lower than the water transfer amount of 37.50 $m^3 s^{-1}$ required by the project.

The big melen water transfer project is most likely to deteriorate water quantity and quality of big melen stream unless the environmental flow requirement conditions determined in this study are met. Future studies are needed to account for changes in water velocity and water depth depending on flow rate along multiple stream cross-sections in a spatially and temporally varying way. Given the coupling of water quantity and quality, changes in water quality at the mouth of water diversion point under the existing load of water pollutants as well as in the interactions between the stream and its riparian zone and discharge point into the sea need to be taken explicitly into account even if the minimum environmental flow requirement is met during the water transfer.

Conclusion

Some additional key issues in seeking an ecosystem-oriented solution to degradation and destruction of riverine ecosystems in a given space and time call for (1) adaptive management of environmental flow requirements and flow regimes at a watershed scale in the face of human-induced disturbances including global climate change as well as uncertainties inherent in scientific understanding; (2) monitoring and prediction of spatially and temporally explicit dynamics of environmental flow requirements based on the integration of advanced capabilities by remote sensing, geographic information system (GIS) and process-based and stochastic hydrological models; (3) risk assessment and valuation of ecological, social and economic implications of human-induced flow regulation; (4) restoration/rehabilitation of damaged riverine ecosystems to an ecologically productive and socially desirable state; and (5) reorientation of public decision- and policy-making in a participatory way towards ensuring coordination at different scales of organization (local, regional, national, international and global) as well as across different institutions so as to avoid the tragedy of the commons.

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